

Nucleon resonances in the $\pi^-p \rightarrow K^0\Lambda$ reaction near threshold

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We investigate the two-body reaction $\pi^-p \rightarrow K^0\Lambda$ within the effective Lagrangian approach and the isobar model. In addition to the “background” contributions from t -channel K^* exchange, u -channel $\Sigma(1192)$ and $\Sigma^*(1385)$ exchanges, and s -channel nucleon pole terms, the contributions from the nucleon resonances $N^*(1535)$, $N^*(1650)$, and $N^*(1720)$ are investigated. It is shown that the inclusion of these nucleon resonances contributions leads to a good description of the experimental total and differential cross sections data at low energy region. The s -channel $N^*(1535)$, $N^*(1650)$, and $N^*(1720)$ resonances and the t -channel K^* exchange give the dominant contributions below $W = 1.76$ GeV, while the s -channel nucleon pole, u -channel $\Sigma(1192)$ and $\Sigma^*(1385)$ exchanges give the minor contributions.

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I. INTRODUCTION

The study of the spectrum of the nucleon resonances and the resonances coupling constants from the available experimental data are two of the most important issues in hadronic physics and they are attracting much attention [1]. In the classical quark models [2–4], a rich spectrum of excited nucleon states is predicted. Many of these nucleon resonances could be identified in πN scattering. However, there are still some of them have not been so far observed.

The strangeness production reaction $\pi^-p \rightarrow K^0\Lambda$ is a good platform to study the properties of the nucleon resonances, especially for those which have significant couplings to πN and $K\Lambda$ channels, because the $\pi^-p \rightarrow K^0\Lambda$ reaction is a pure isospin $I = 1/2$ two-body reaction channel in meson-nucleon dynamics, and there are no contributions from the isospin $I = 3/2$ $\Delta(1232)$ baryons. Hence, lots of experimental data have been accumulated [5–8], where the total and differential cross sections of $\pi^-p \rightarrow K^0\Lambda$ reaction are measured.

In response to this wealth of data, the theoretical activity has run in parallel. In Ref. [9], the two-body reaction $\pi^-p \rightarrow K^0\Lambda$ is investigated using the partial wave amplitudes which are constructed from the available experimental data. The total and differential cross sections of $\pi^-p \rightarrow K^0\Lambda$ reaction can be well described by using these amplitudes, which are essential for obtaining spin-flip and spin non-flip amplitudes [10]. But, from these amplitudes, it is difficult to get clear properties of some nucleon resonances, because the partial wave amplitudes could have contributions from nucleon resonances with different spins, and individual contributions are more difficult to pin down. This deficiency is also shown in

Ref. [11] where the reactions $\pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ are studied simultaneously within an analytic, unitary, coupled-channel approach. Moreover, it is pointed out that there are ambiguities of the $\pi^-p \rightarrow K^0\Lambda$ scattering amplitudes obtained from the partial wave analysis, when only the observables of the differential cross section and polarization are measured [12].

The role played by the nucleon resonance $N^*(1535)$, which has proved to be a controversial resonance for many years, in the $K\Lambda$ production is crucial. The $N^*(1535)$ couples strongly to the ηN channel [13] but a large $N^*(1535)K\Lambda$ coupling has also been deduced [14–17] through the analysis of BES data on $J/\psi \rightarrow \bar{p}K^+\Lambda$ decay [18] and COSY data on the $pp \rightarrow p\Lambda K^+$ reaction near threshold [19]. In Refs. [20–23], the analyses of recent SAPHIR [24, 25] and CLAS [26] $\gamma p \rightarrow K^+\Lambda$ data also indicate a large coupling of the $N^*(1535)$ resonance to the $K\Lambda$ channel. Furthermore, in a chiral unitary coupled channel model it is found that the $N^*(1535)$ resonance is dynamically generated, with its mass, width and branching ratios in fair agreement with experiment [14, 27–30]. This approach shows that the couplings of the $N^*(1535)$ resonance to $K\Lambda$ channel could be large compared to those for πN . We wish to argue in this work that the $N^*(1535)$ resonance might play a much wide role in associated strangeness production of $\pi^-p \rightarrow K^0\Lambda$ reaction.

In the present work, we study the two-body reaction $\pi^-p \rightarrow K^0\Lambda$ within an effective Lagrangian approach and the isobar model, which is an important theoretical method for describing various processes in the resonances production region [31–40]. In addition to the background contributions from t -channel K^* exchange, u -channel $\Sigma(1192)$ and $\Sigma^*(1385)$ exchange, and s -channel nucleon pole terms, we also investigate the contributions from nucleon resonances $N^*(1535)$, $N^*(1650)$, and $N^*(1720)$, which have significant couplings to πN and $K\Lambda$ channels [13].

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This article is organized as follows. In Sect. II we present the formalism and ingredients required for the calculation. The numerical results and discussions are given in Sect. III. A short summary is given in the last section.

II. FORMALISM AND INGREDIENTS

In this section, we introduce the theoretical formalism and ingredients for calculating the $\pi^- p \rightarrow K^0 \Lambda$ reaction by using the effective Lagrangian approach and the isobar model. In the following equations, we use N_1^* , N_2^* , and N_3^* , which denote the $N^*(1535)$, $N^*(1650)$, and $N^*(1720)$, respectively.

The basic tree level Feynman diagrams for the $\pi^- p \rightarrow K^0 \Lambda$ reaction are depicted in Fig. 1. These include s -channel nucleon pole and nucleon resonances process [Fig. 1 (a)], t -channel K^* exchange [Fig. 1 (b)], and u -channel $\Sigma(1192)$ and $\Sigma^*(1385)(\equiv \Sigma^*)$ exchanges [Fig. 1 (c)].

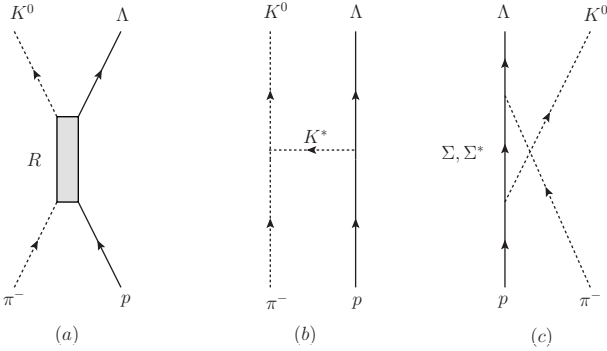


FIG. 1: Feynman diagrams for the reaction $\pi^- p \rightarrow K^0 \Lambda$. The contributions from s -channel nucleon resonance t -channel K^* exchange, and u -channel $\Sigma(1192)$ and $\Sigma^*(1385)$ exchange are considered.

To evaluate the invariant scattering amplitudes corresponding to these diagrams shown in Fig. 1, the effective Lagrangian densities for relevant interaction vertexes are needed. Following Refs. [41–46], the Lagrangian densities used in present work are,

$$\mathcal{L}_{\pi NN} = -\frac{g_{\pi NN}}{2m_N} \bar{N} \gamma_5 \gamma_\mu \vec{\tau} \cdot \partial^\mu \vec{\pi} N, \quad (1)$$

$$\mathcal{L}_{\pi NN_1^*} = -g_{\pi NN_1^*} \bar{N}_1^* \vec{\tau} \cdot \vec{\pi} N + h.c., \quad (2)$$

$$\mathcal{L}_{\pi NN_2^*} = -g_{\pi NN_2^*} \bar{N}_2^* \vec{\tau} \cdot \vec{\pi} N + h.c., \quad (3)$$

$$\mathcal{L}_{\pi NN_3^*} = \frac{g_{\pi NN_3^*}}{m_\pi} \bar{N}_3^{*\mu} \vec{\tau} \cdot \partial_\mu \vec{\pi} N + h.c., \quad (4)$$

$$\mathcal{L}_{K\Lambda N} = -\frac{g_{K\Lambda N}}{m_N + m_\Lambda} \bar{N} \gamma_5 \gamma_\mu \partial^\mu K \Lambda + h.c., \quad (5)$$

$$\mathcal{L}_{K\Lambda N_1^*} = -g_{K\Lambda N_1^*} \bar{N}_1^* K \Lambda + h.c., \quad (6)$$

$$\mathcal{L}_{K\Lambda N_2^*} = -g_{K\Lambda N_2^*} \bar{N}_2^* K \Lambda + h.c., \quad (7)$$

$$\mathcal{L}_{K\Lambda N_3^*} = \frac{g_{K\Lambda N_3^*}}{m_K} \bar{N}_3^{*\mu} \partial_\mu K \Lambda + h.c., \quad (8)$$

for s -channel nucleon pole and nucleon resonances, $N^*(1535)$, $N^*(1650)$, $N^*(1720)$ exchange terms, and

$$\mathcal{L}_{K^* \Lambda N} = -g_{K^* \Lambda N} \bar{N} \gamma^\mu K_\mu^* \Lambda + h.c., \quad (9)$$

$$\mathcal{L}_{K^* K \pi} = -g_{K^* K \pi} K_\mu^* (\partial^\mu \bar{K} \vec{\tau} \cdot \vec{\pi} - \bar{K} \vec{\tau} \cdot \partial^\mu \vec{\pi}), \quad (10)$$

for the t -channel K^* exchange process, while

$$\mathcal{L}_{KN\Sigma} = -\frac{g_{KN\Sigma}}{m_N + m_\Sigma} \bar{N} \gamma_5 \gamma_\mu \partial^\mu K \vec{\tau} \cdot \vec{\Sigma} + h.c., \quad (11)$$

$$\mathcal{L}_{\pi\Sigma\Lambda} = -\frac{g_{\pi\Sigma\Lambda}}{m_\Lambda + m_\Sigma} \bar{\Lambda} \gamma_5 \gamma_\mu \partial^\mu \vec{\pi} \cdot \vec{\Sigma} + h.c., \quad (12)$$

$$\mathcal{L}_{KN\Sigma^*} = \frac{g_{KN\Sigma^*}}{m_K} \bar{\Sigma}^{*\mu} \partial_\mu K N + h.c., \quad (13)$$

$$\mathcal{L}_{\pi\Lambda\Sigma^*} = \frac{g_{\pi\Lambda\Sigma^*}}{m_\pi} \bar{\Sigma}^{*\mu} \vec{\tau} \cdot \partial_\mu \vec{\pi} \Lambda + h.c., \quad (14)$$

for the u -channel $\Sigma(1192)$ and $\Sigma^*(1385)$ exchange diagrams.

For the coupling constants in the above Lagrangian densities for t -channel and u -channel processes, we take $g_{\pi NN} = 13.45$ (obtained by $g_{\pi NN}^2/4\pi = 14.4$), $g_{\rho NN} = 3.25$ (obtained by $g_{\rho NN}^2/4\pi = 0.84$), $g_{\rho\pi\pi} = 6.04$ (obtained by $g_{\rho\pi\pi}^2/4\pi = 2.90$), and $g_{\Delta N\pi} = 2.18$ ¹, which are used in Ref. [11]. The others are obtained by $SU(3)$ flavor symmetry as shown in Table I.

TABLE I: The coupling constants for t -channel and u -channel processes used in the present study, which are obtained by the $SU(3)$ flavor symmetry with $\alpha_1 = 0.4$ and $\alpha_2 = 1.15$.

Vertex	g	Value	Vertex	g	Value
$KN\Lambda$	$-\frac{g_{\pi NN}}{\sqrt{3}}(1+2\alpha_1)$	-13.98	$K^*K\pi$	$-\frac{g_{\rho\pi\pi}}{2}$	-3.02
$KN\Sigma$	$g_{\pi NN}(1-2\alpha_1)$	2.69	$\Sigma^*\pi\Lambda$	$\frac{g_{\Delta\pi N}}{\sqrt{2}}$	1.54
$\pi\Lambda\Sigma$	$\frac{2g_{\rho NN}}{\sqrt{3}}(1-\alpha_1)$	9.32	Σ^*KN	$-\frac{g_{\Delta\pi N}}{\sqrt{6}}$	-0.89
$K^*\Lambda N$	$-\frac{g_{\rho NN}}{\sqrt{3}}(1+2\alpha_2)$	-6.19			

Besides, the coupling constants for the s -channel nucleon resonance exchange processes, are obtained from

¹ Which is obtained by the partial decay width of Δ to πN .

the partial decay widths,

$$\Gamma[N_1^* \rightarrow \pi N] = \frac{3g_{\pi NN_1^*}^2 (E_N + m_N)}{4\pi m_{N_1^*}} |\vec{p}_1^N|, \quad (15)$$

$$\Gamma[N_2^* \rightarrow \pi N] = \frac{3g_{\pi NN_2^*}^2 (E_N + m_N)}{4\pi m_{N_2^*}} |\vec{p}_2^N|, \quad (16)$$

$$\Gamma[N_2^* \rightarrow K \Lambda] = \frac{g_{K \Lambda N_2^*}^2 (E_\Lambda + m_\Lambda)}{4\pi m_{N_2^*}} |\vec{p}_2^\Lambda|, \quad (17)$$

$$\Gamma[N_3^* \rightarrow \pi N] = \frac{3g_{\pi NN_3^*}^2 (E_N + m_N)}{12\pi m_{N_3^*} m_\pi^2} |\vec{p}_3^N|^3, \quad (18)$$

$$\Gamma[N_3^* \rightarrow K \Lambda] = \frac{g_{K \Lambda N_3^*}^2 (E_\Lambda + m_\Lambda)}{12\pi m_{N_3^*} m_K^2} |\vec{p}_3^\Lambda|^3, \quad (19)$$

with

$$|\vec{p}_i^N| = \frac{\lambda^{\frac{1}{2}}(m_{N_i^*}^2, m_\pi^2, m_N^2)}{2m_{N_i^*}}, \quad (20)$$

$$|\vec{p}_i^\Lambda| = \frac{\lambda^{\frac{1}{2}}(m_{N_i^*}^2, m_K^2, m_\Lambda^2)}{2m_{N_i^*}}, \quad (21)$$

where λ is the Källen function with $\lambda(x, y, z) = (x - y - z)^2 - 4yz$.

With masses and partial decay widths of the nucleon resonances, the strong coupling constants of nucleon resonances $N^*(1535)$, $N^*(1650)$ and $N^*(1720)$ are obtained as listed in Table II. Moreover, the strong coupling constants $g_{K \Lambda N^*(1535)}$ is a free parameter, which will be determined by fitting to the experimental data of the $\pi^- p \rightarrow K^0 \Lambda$ reaction.

Due to the fact that the relevant hadrons are not point-like particles, form factors are included. In our present calculation, we adopt the following form factors,

$$F_i(q_i^2) = \left[\frac{\Lambda_i^4}{\Lambda_i^4 + (q_i^2 - m_i^2)^2} \right]^n, i = s, t, u, R \quad (22)$$

$$\text{with } \begin{cases} q_s^2 = q_R^2 = s, q_t^2 = t, q_u^2 = u, \\ M_s = m_N, M_R = M_{N^*}, \\ M_t = m_{K^*}, \\ M_u = m_\Sigma \text{ or } m_{\Sigma^*}, \end{cases}$$

with $n = 1$ for s -channel $N^*(1535)$ and $N^*(1650)$, and $n = 2$ for s -channel $N^*(1720)$, nucleon pole, t -channel K^* exchange, u -channel Σ hyperon pole, and $\Sigma^*(1385)$ exchange. The s , t and u are the Lorentz-invariant Mandelstam variables, while $q_s = q_R = p_1 + p_2 = p_3 + p_4$, $q_t = p_1 - p_3$, and $q_u = p_4 - p_1$ are the four-momenta of the intermediate particle in the s , t , and u -channel, and p_1 , p_2 , p_3 and p_4 are the four momenta of π^- , p , K^0 and Λ , respectively. For the cutoff parameters, they will be determined by fitting them to the experimental data.

For propagators $G_{1/2}(p)$ of the spin-1/2 particle and $G_{3/2}^{\mu\nu}(p)$ of the spin-3/2 particle, we adopt the simple

Breit-Wigner formula,,

$$G_{1/2}(p) = i \frac{\not{p} + M}{p^2 - M^2 + iM\Gamma^{\text{full}}}, \quad (23)$$

$$G_{3/2}^{\mu\nu}(p) = i \frac{(\not{p} + M)P^{\mu\nu}(p)}{p^2 - M^2 + iM\Gamma^{\text{full}}}, \quad (24)$$

with

$$P^{\mu\nu}(p) = g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{1}{3M}(\gamma^\mu p^\nu - \gamma^\nu p^\mu) - \frac{2}{3M^2}p^\mu p^\nu, \quad (25)$$

where M and Γ^{full} stand for the mass and full decay width of the corresponding resonances. It is worth to note that for s -channel nucleon pole and u -channel $\Sigma(1192)$ and $\Sigma^*(1385)$ exchange, we take $\Gamma^{\text{full}} = 0$.

While for the K^* meson propagator $G_{K^*}^{\mu\nu}(p)$, we take

$$G_{K^*}^{\mu\nu}(p) = i \frac{-g^{\mu\nu} + p^\mu p^\nu / m_{K^*}^2}{p^2 - m_{K^*}^2}. \quad (26)$$

Then the total invariant scattering amplitude for $\pi^- p \rightarrow K^0 \Lambda$ reaction, according to these contributions shown in Fig. 1, can be written as,

$$\mathcal{M}_{\pi^- p \rightarrow K^0 \Lambda} = \mathcal{M}_{\text{BG}} + e^{i\theta_1} \mathcal{M}_{N^*(1535)} + e^{i\theta_2} \mathcal{M}_{N^*(1650)} + e^{i\theta_3} \mathcal{M}_{N^*(1720)}, \quad (27)$$

with

$$\mathcal{M}_{\text{BG}} = \mathcal{M}_N + \mathcal{M}_{K^*} + \mathcal{M}_\Sigma + \mathcal{M}_{\Sigma^*}. \quad (28)$$

Note that we have employed the phase factor for the nucleon resonances $e^{i\theta_{1,2,3}}$, since we can not determine the phase for the nucleon resonances within our model. Thus, these phase angles θ will be determined to reproduce the experimental data.

With the above effective Lagrangian densities, we can straightforwardly evaluate the following invariant scattering amplitudes, corresponding to the Feynman diagrams in Fig. 1:

$$\mathcal{M}_{N_{1,2}^*} = \sqrt{2} g_{\pi NN_{1,2}^*} g_{K \Lambda N_{1,2}^*} F_R(q_R^2) \bar{u}_\Lambda(p_4, s_\Lambda) G_{1/2}(q_R) u_p(p_2, s_p), \quad (29)$$

$$\mathcal{M}_{N_3^*} = - \frac{\sqrt{2} g_{\pi NN_3^*} g_{K \Lambda N_3^*} F_R(q_R^2)}{m_K m_\pi} \bar{u}_\Lambda(p_4, s_\Lambda) p_{3\mu} G_{3/2}^{\mu\nu}(q_R) p_{1\nu} u_p(p_2, s_p), \quad (30)$$

$$\mathcal{M}_N = \frac{\sqrt{2} g_{\pi NN} g_{K \Lambda N} F_N(q_s^2)}{2m_N(m_\Lambda + m_N)} \bar{u}_\Lambda(p_4, s_\Lambda) \not{p}_3 \gamma_5 G_{1/2}(q_s) \gamma_5 \not{p}_1 u_p(p_2, s_p), \quad (31)$$

$$\mathcal{M}_{K^*} = -i g_{K^* \Lambda N} g_{K^* K \pi} F_t(q_t^2) \bar{u}_\Lambda(p_4, s_\Lambda) \gamma_\mu G_{K^*}^{\mu\nu}(q_t) (p_{3\nu} + p_{1\nu}) u_p(p_2, s_p), \quad (32)$$

$$\mathcal{M}_\Sigma = -g_{\pi \Lambda \Sigma} g_{K N \Sigma} F_u(q_u^2) \bar{u}_\Lambda(p_4, s_\Lambda) \gamma_5 G_{1/2}(q_u) \gamma_5 u_p(p_2, s_p), \quad (33)$$

$$\mathcal{M}_{\Sigma^*} = - \frac{g_{\pi \Lambda \Sigma^*} g_{K N \Sigma^*} F_u(q_u^2)}{m_K m_\pi} \bar{u}_\Lambda(p_4, s_\Lambda) p_{1\mu} G_{3/2}^{\mu\nu}(q_u) p_{3\nu} u_p(p_2, s_p), \quad (34)$$

TABLE II: Relevant nucleon resonance coupling constants used in present work. The widths and branching ratios are taken from the Particle Data Group [13].

Resonance (J^P)	Mass (GeV)	Width (GeV)	Decay channel	Branching ratio	Adopted value	$g^2/4\pi$
$N(1535)(\frac{1}{2}^-)$	1.535	0.15	$N\pi$	$0.35 \sim 0.55$	0.45	0.037
$N(1650)(\frac{1}{2}^-)$	1.655	0.15	$N\pi$	$0.50 \sim 0.90$	0.70	0.052
			ΛK	$0.03 \sim 0.11$	0.07	0.045
$N(1720)(\frac{3}{2}^+)$	1.720	0.25	$N\pi$	$0.08 \sim 0.14$	0.11	0.0022
			ΛK	$0.01 \sim 0.15$	0.08	0.52

where s_p and s_Λ are the polarization variables of proton and Λ .

The unpolarized differential cross section in the center-of-mass (c.m.) frame for the $\pi^- p \rightarrow K^0 \Lambda$ reaction reads,

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{2\pi d\cos\theta} = \frac{m_\Lambda m_N}{32\pi^2 s} \frac{|\vec{p}_3^{\text{c.m.}}|}{|\vec{p}_1^{\text{c.m.}}|} |\mathcal{M}_{\pi^- p \rightarrow K^0 \Lambda}|^2, \quad (35)$$

with θ is the polar scattering angle of outgoing K^0 meson, and $\vec{p}_1^{\text{c.m.}}$ and $\vec{p}_3^{\text{c.m.}}$ are the π^- and K^0 mesons c.m. three momenta. The differential cross section $d\sigma/d\cos\theta$ depends on $W = \sqrt{s}$ and also on $\cos\theta$.

As mentioned above, the model accounts for a total of three mechanisms: s -channel nucleon pole and N^* resonances terms, t -channel K^* exchange, and the u -channel $\Sigma(1192)$ pole and $\Sigma^*(1385)$ contributions. In principle, the free parameters of the model are: i) relative phases between different contributions, ii) the cut off parameters, $\Lambda_N = \Lambda_t = \Lambda_u \equiv \Lambda_B$, and $\Lambda_{N^*(1535)} = \Lambda_{N^*(1650)} = \Lambda_{N^*(1720)} \equiv \Lambda_R$, and iii) the coupling constant $g_{N^*(1535)K\Lambda}$.

In the next section, we will fit the parameters of the model to the low energy differential cross section data of the $\pi^- p \rightarrow K^0 \Lambda$ reaction by using the MINUIT fitting program.

III. RESULTS AND DISCUSSION

First, by including the contributions from s -channel nucleon pole, $N^*(1535)$, $N^*(1650)$ and $N^*(1720)$, t -channel K^* exchange, and u -channel $\Sigma(1192)$ and $\Sigma(1385)$ exchange terms, we perform a four-parameter $[g_{K\Lambda N^*(1535)}, \theta_1, \theta_2, \theta_3]$ χ^2 fit (Fit I) to the experimental data [5–7] on differential cross sections of $\pi^- p \rightarrow K^0 \Lambda$ reaction. The experimental data base contains differential cross sections at 20 energy points from 3 different experiments, and there is a total of 385 data points below $W = 1.76$ GeV. Second, for showing the important role played by the $N^*(1535)$ resonance, we have also performed another best fit, where the s -channel $N^*(1535)$ resonance has been switched off (Fit II).

The fitted parameters of Fit I and Fit II are compiled in Table III. The resultant χ^2/dof of Fit I is 2.3, while for the Fit II, it is 3.4, which is turn out to be larger, since we have ignored the important contributions from the $N^*(1535)$ resonance. From the the fitted

result, $g_{K\Lambda N^*(1535)} = 1.31 \pm 0.08$, we obtain the ratio $R \equiv |g_{K\Lambda N^*(1535)}/g_{\eta NN^*(1535)}| = 0.71 \pm 0.10$ with the value of $g_{\eta NN^*(1535)} = 1.85 \pm 0.24$ that is obtained with the partial decay width of $N^*(1535) \rightarrow N\eta$. This value is smaller than the one 1.3 ± 0.3 obtained in Ref. [15] by analyzing the $J/\psi \rightarrow \bar{p}K^+\Lambda$ and $J/\psi \rightarrow \bar{p}\eta p$ experimental data. This is because in the work of Ref. [15], the energy dependent width for the $N^*(1535)$ resonance is used, which will decrease the contribution from the propagator of $N^*(1535)$ resonance above the $K\Lambda$ threshold and make the coupling strength of the $N^*(1535)$ resonance to the $K\Lambda$ channel larger.² In contrast with the energy dependent width as in Ref. [15], in the present work we use a constant total decay width for $N^*(1535)$ resonance since the $K\Lambda$ channel is opened. Nevertheless, the values of this ratio obtained in the previous works are widely scattered. For instance, $R = 0.460 \pm 0.172$ has been determined from the latest and largest photoproduction database by using the isobar model. Similar results, $R = 0.5 \sim 0.7$ were obtained in Ref. [17] from the J/ψ decays within the chiral unitary approach and $R = 0.42 \sim 0.73$ was obtained in Ref. [47] by the partial wave analysis of kaon photonproduction. In Ref. [48] the result of the s -wave πN scattering analysis within a unitarized chiral effective Lagrangian indicates that $|g_{K\Lambda N^*(1535)}|^2 > |g_{\eta NN^*(1535)}|^2$, whereas a coupled-channels calculation predicted a value of $R = 0.8 \sim 2.6$ [21].

TABLE III: Fitted parameters of Fit I and Fit II.

Parameters	Fit I	Fit II
Λ_B [GeV]	0.86 ± 0.02	0.80 ± 0.01
Λ_R [GeV]	0.85 ± 0.04	0.78 ± 0.03
$g_{K\Lambda N^*(1535)}$	1.31 ± 0.08	–
θ_1	2.59 ± 0.08	–
θ_2	1.40 ± 0.08	0.60 ± 0.06
θ_3	0.26 ± 0.07	-0.94 ± 0.05
χ^2/dof	2.3	3.4

The differential distributions $d\sigma/d\Omega$ calculated with

² Similar statement can be also found in Ref. [45] for the case of the $\Lambda(1405)$.

the Fit I best-fit parameters are shown in Fig. 2 as a function of $\cos\theta$ and for various π^-p invariant mass intervals. The contributions from different mechanisms are shown separately. Thus, we split the full result into four main contributions: effective Lagrangian approach background, s -channel $N^*(1535)$, $N^*(1650)$ and $N^*(1720)$. The first one corresponds to the t -channel K^* exchange, s -channel nucleon pole, and u -channel $\Sigma(1192)$ hyperon pole and $\Sigma^*(1385)$ terms. We find an overall good description of the data for the whole range of measured π^-p invariant masses below 1.76 GeV, and the contributions from the above three main mechanisms are all significant to reproduce the current experimental data.

Our best result of the total cross sections of $\pi^-p \rightarrow K^0\Lambda$ reaction as a function of the invariant mass of the π^-p system are shown in Fig. 3 compared with the experimental data [8]. There, we see that we can describe the total cross section data quite well. As mentioned above, the $N^*(1535)$ resonance and $N^*(1650)$ resonance couple strongly to the $K\Lambda$ channel. Indeed, the total cross section of $\pi^-p \rightarrow K^0\Lambda$ show a strong S -wave contributions close to the reaction threshold and also a little bit beyond. From Fig. 3, it is seen that the contribution from $N^*(1650)$ (blue dashed curve) is predominant at a very wide energy region, and the contribution from the $N^*(1535)$ (red solid curve) is significant from the reaction threshold till $W < 1.66$ GeV, while the contributions from t -channel K^* exchange and s -channel $N^*(1720)$ are dominant above $W > 1.7$ GeV. The s -channel nucleon pole and u -channel contributions are too small to be shown in Fig. 3 and can be neglected.

It is worthy to note that we do not consider the contribution from the nucleon resonance $N^*(1710)$, which is mostly required by the πN inelastic scattering data. The role of this resonance in the context of different partial-wave analyses has been discussed extensively in Refs. [11, 49]. In the analysis of the $\pi^-p \rightarrow n\eta$ reaction, a $N^*(1710)$ resonance is needed [49]. But, it is pointed out in Ref. [11] that in the analysis of the $\pi^-p \rightarrow K^0\Lambda$ reaction, there is an interplay between the $N^*(1720)$ and $N^*(1710)$ and individual contributions are difficult to pin down. Moreover, the $N^*(1710)$ resonance appears in the three-body hadronic calculations [50, 51] and also could be a dynamically generated resonance [52, 53]. On the other hand, a Bayesian analysis of the world data on $\gamma p \rightarrow K^+\Lambda$ reaction [54] show that there is no sig-

nificant contribution of the $N^*(1710)$ resonance to the $\gamma p \rightarrow K^+\Lambda$ reaction. Because of those doubts of this resonance, we ignore its contribution in our present calculations.

IV. SUMMARY

In this paper, the $\pi^-p \rightarrow K^0\Lambda$ reaction is investigated within an effective Lagrangian approach and the isobar model. This channel is known to receive significant non-resonant contributions which complicates the extraction of N^* information. In addition to the background contributions from the s -channel nucleon pole, t -channel K^* exchange, u -channel $\Sigma(1192)$ and $\Sigma^*(1385)$ exchanges, we also consider the contributions from s -channel nucleon resonances $N^*(1535)$, $N^*(1650)$, and $N^*(1720)$. From χ^2 -fits to the available experimental data for the $\pi^-p \rightarrow K^0\Lambda$ reaction, we get the appropriate parameters which describe the total and differential cross sections well. Our results show that the inclusion of the nucleon resonances $N^*(1535)$, $N^*(1650)$, and $N^*(1720)$ can lead to a good description of the low energy experimental total and differential cross sections data of $\pi^-p \rightarrow K^0\Lambda$ reaction. The contribution from each individual resonance to the total and differential cross sections below $\sqrt{s} = 1.76$ GeV are also presented. The contributions from those nucleon resonances and the t -channel K^* exchange are dominant, while s -channel nucleon pole and the u -channel $\Sigma(1192)$ and $\Sigma^*(1385)$ exchange give the minor contributions and can be neglected.

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-
- [1] E. Klempt and J. M. Richard, Rev. Mod. Phys. **82**, 1095 (2010).
 - [2] N. Isgur and G. Karl, Phys. Rev. D **18**, 4187 (1978).
 - [3] S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986).
 - [4] U. Loring, B. C. Metsch and H. R. Petry, Eur. Phys. J. A **10**, 395 (2001).
 - [5] T. M. Knasel, J. Lindquist, B. Nelson, R. L. Sumner, E. C. Swallow, R. Winston, D. M. Wolfe and P. R. Phillips *et al.*, Phys. Rev. D **11**, 1 (1975).
 - [6] R. D. Baker, J. A. Blissett, I. J. Bloodworth, T. A. Broome, G. Conforto, J. C. Hart, C. M. Hughes and R. W. Kraemer *et al.*, Nucl. Phys. B **141**, 29 (1978).
 - [7] L. Bertanza, P. L. Connolly, B. B. Culwick, F. R. Eisler, T. Morris, R. B. Palmer, A. Prodell and N. P. Samios, Phys. Rev. Lett. **8**, 332 (1962).
 - [8] A. Baldini, V. Flaminio, W. G. Moorhead, D. R. O. Morrison and H. Schopper, BERLIN, GERMANY: SPRINGER (1988) 409 P. (LANDOLT-BOERNSTEIN.

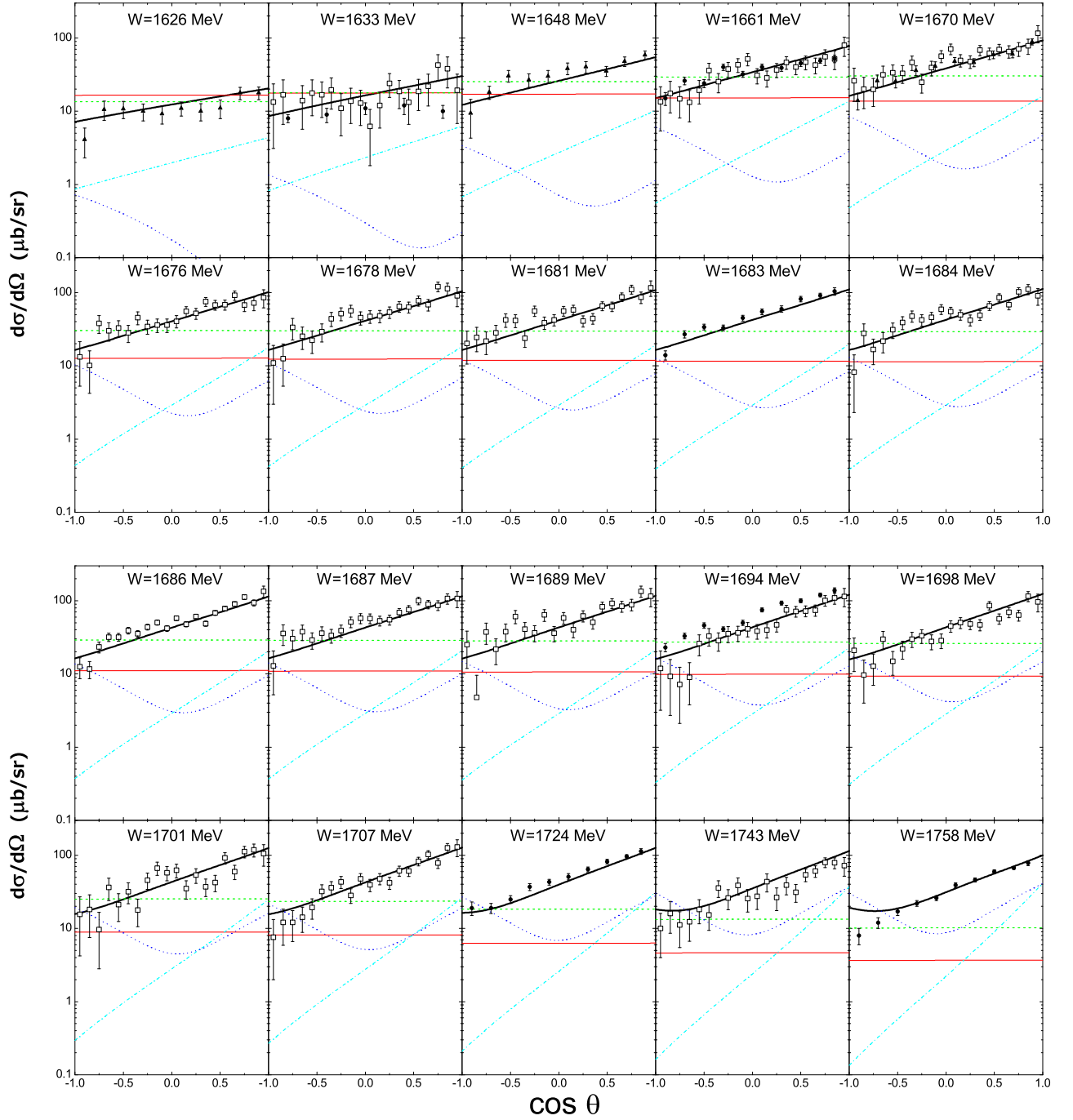


FIG. 2: (Color online) Fit I differential cross sections for the reaction $\pi^-p \rightarrow K^0\Lambda$ in the center of mass frame as a function of $\cos\theta$ at different π^-p invariant mass intervals compared with the experimental data from Ref. [5] (squares), Ref. [6] (circles), Ref. [7] (triangles). The cyan dashed-dotted, red solid, green dashed, and blue dotted curves stand for the contributions from the the background (s -channel nucleon pole, t -channel K^* exchange and u -channel Σ and $\Sigma^*(1385)$ exchange terms), s -channel $N^*(1535)$, $N^*(1650)$, and $N^*(1720)$ terms, respectively. The bold black solid lines represent the results obtained from the full model.

NEW SERIES, 1/12B).

- [9] A. Sibirtsev, J. Haidenbauer, H. -W. Hammer and S. Krewald, Eur. Phys. J. A **27**, 269 (2006).
 [10] M. Sotona and J. Zofka, Prog. Theor. Phys. **81**, 160

(1989).

- [11] D. Ronchen, M. Doring, F. Huang, H. Haberzettl, J. Haidenbauer, C. Hanhart, S. Krewald and U. - G. Meissner *et al.*, Eur. Phys. J. A **49**, 44 (2013).

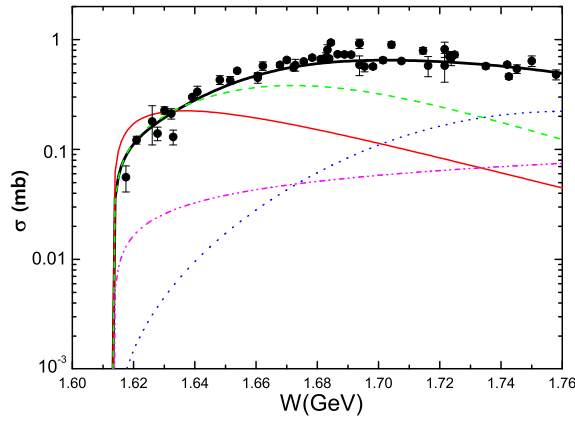


FIG. 3: (Color online) Total cross section of the $\pi^-p \rightarrow K^0\Lambda$ reaction as a function of the invariant mass of π^-p system with the fitted parameters of Fit I. The experimental data are taken from Ref. [8]. The bold black solid lines represent the results from the full model, while the contributions from t -channel K^* exchange and s -channel $N^*(1535)$, $N^*(1650)$, $N^*(1720)$ terms are shown by the magenta dash-dot-dotted, red solid, green dashed and blue dotted curves, respectively.

- [12] A. V. Anisovich, R. Beck, E. Klempt, V. A. Nikonov, A. V. Sarantsev, U. Thoma and Y. Wunderlich, Eur. Phys. J. A **49**, 121 (2013).
- [13] K.A. Olive et al. (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014).
- [14] C. Garcia-Recio, M. F. M. Lutz and J. Nieves, Phys. Lett. B **582**, 49 (2004).
- [15] B. C. Liu and B. S. Zou, Phys. Rev. Lett. **96**, 042002 (2006).
- [16] B. C. Liu and B. S. Zou, Phys. Rev. Lett. **98**, 039102 (2007).
- [17] L. S. Geng, E. Oset, B. S. Zou and M. Doring, Phys. Rev. C **79**, 025203 (2009).
- [18] H. X. Yang [BES Collaboration], Int. J. Mod. Phys. A **20**, 1985 (2005).
- [19] P. Kowina, M. Wolke, H. H. Adam, A. Budzanowski, R. Czyzykiewicz, D. Grzonka, J. Haidenbauer and M. Janusz *et al.*, Eur. Phys. J. A **22**, 293 (2004).
- [20] G. Penner and U. Mosel, Phys. Rev. C **66**, 055211 (2002).
- [21] G. Penner and U. Mosel, Phys. Rev. C **66**, 055212 (2002).
- [22] V. Shklyar, H. Lenske and U. Mosel, Phys. Rev. C **72**, 015210 (2005).
- [23] B. Julia-Diaz, B. Saghai, T.-S. H. Lee and F. Tabakin, Phys. Rev. C **73**, 055204 (2006).
- [24] M. Q. Tran *et al.* [SAPHIR Collaboration], Phys. Lett. B **445**, 20 (1998).
- [25] K. H. Glander, J. Barth, W. Braun, J. Hannappel, N. Jopen, F. Klein, E. Klempt and R. Lawall *et al.*, Eur. Phys. J. A **19**, 251 (2004).
- [26] R. Nasseripour *et al.* [CLAS Collaboration], Phys. Rev. C **77**, 065208 (2008).
- [27] N. Kaiser, T. Waas and W. Weise, Nucl. Phys. A **612**, 297 (1997).
- [28] T. Inoue, E. Oset and M. J. Vicente Vacas, Phys. Rev. C **65**, 035204 (2002).
- [29] J. Nieves and E. Ruiz Arriola, Phys. Rev. D **64**, 116008 (2001).
- [30] M. Doring and K. Nakayama, Eur. Phys. J. A **43**, 83 (2010).
- [31] K. Tsushima, S. W. Huang and A. Faessler, Austral. J. Phys. **50**, 35 (1997).
- [32] K. Tsushima, A. Sibirtsev, A. W. Thomas and G. Q. Li, Phys. Rev. C **59**, 369 (1999) [Erratum-ibid. C **61**, 029903 (2000)].
- [33] R. Shyam, Phys. Rev. C **60**, 055213 (1999).
- [34] J. J. Xie, B. S. Zou and H. C. Chiang, Phys. Rev. C **77**, 015206 (2008).
- [35] J. P. Dai, P. N. Shen, J. J. Xie and B. S. Zou, Phys. Rev. D **85**, 014011 (2012).
- [36] B. C. Liu and J. J. Xie, Phys. Rev. C **85**, 038201 (2012).
- [37] B. C. Liu and J. J. Xie, Phys. Rev. C **86**, 055202 (2012).
- [38] Q. F. Lü, X. H. Liu, J. J. Xie and D. M. Li, Mod. Phys. Lett. A **29**, 1450012 (2014).
- [39] Q. F. Lü, J. J. Xie and D. M. Li, Phys. Rev. C **90**, 034002 (2014).
- [40] J. J. Xie, E. Wang and B. S. Zou, Phys. Rev. C **90**, 025207 (2014).
- [41] G. Janssen, K. Holinde and J. Speth, Phys. Rev. C **54**, 2218 (1996).
- [42] J. J. Xie, C. Wilkin and B. S. Zou, Phys. Rev. C **77**, 058202 (2008).
- [43] M. Doring, C. Hanhart, F. Huang, S. Krewald, U. - G. Meissner and D. Ronchen, Nucl. Phys. A **851**, 58 (2011).
- [44] T. Mart, Phys. Rev. C **87**, 042201 (2013).
- [45] J. J. Xie, B. C. Liu and C. S. An, Phys. Rev. C **88**, 015203 (2013).
- [46] J. J. Xie and B. C. Liu, Phys. Rev. C **87**, 045210 (2013).
- [47] A. V. Sarantsev, V. A. Nikonov, A. V. Anisovich, E. Klempt and U. Thoma, Eur. Phys. J. A **25**, 441 (2005).
- [48] P. C. Bruns, M. Mai and U. G. Meissner, Phys. Lett. B **697**, 254 (2011).
- [49] S. Ceci, A. Svarc and B. Zauner, Phys. Rev. Lett. **97**, 062002 (2006).
- [50] K. P. Khemchandani, A. Martinez Torres and E. Oset, Eur. Phys. J. A **37**, 233 (2008).
- [51] A. Martinez Torres, K. P. Khemchandani and E. Oset, Phys. Rev. C **79**, 065207 (2009).
- [52] N. Suzuki, B. Julia-Diaz, H. Kamano, T.-S. H. Lee, A. Matsuyama and T. Sato, Phys. Rev. Lett. **104**, 042302 (2010).
- [53] H. Kamano, S. X. Nakamura, T.-S. H. Lee and T. Sato, Phys. Rev. C **81**, 065207 (2010).
- [54] L. De Cruz, T. Vrancx, P. Vancraeyveld and J. Ryckebusch, Phys. Rev. Lett. **108**, 182002 (2012).